Energy scaling of nanosecond gain-switched Cr^{2+}:ZnSe lasers

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ABSTRACT

In this paper, we report record nanosecond output energies of gain-switched Cr:ZnSe lasers pumped by Q-switched Cr:Tm:Ho:YAG (100 ns @ 2.096 μm) and Raman shifted Nd:YAG lasers (7 ns @ 1.906 μm). In these experiments we used Brewster cut Cr:ZnSe gain elements with a chromium concentration of 8×10^{18} cm^{-3}. Under Cr:Tm:Ho:YAG pumping, the first Cr:ZnSe laser demonstrated 3.1 mJ of output energy, 52% slope efficiency and 110 nm linewidth centered at a wavelength of 2.47 μm. Maximum output energy of the second Cr:ZnSe laser reached 10.1 mJ under H_2 Raman shifted Nd:YAG laser pumping. The slope efficiency estimated from the input-output data was 47%.

Keywords: infrared laser, solid-state lasers, chromium, gain-switched

1. INTRODUCTION

Since the first demonstration of the laser 50 years ago [1], incrementally shorter pulses and higher mid-IR pulse energies have been demonstrated [2]. Divalent chromium (Cr^{2+}) is a group 6 transition metal (TM) and has been selected as the lasing transition ion because of its broad tunability in ZnSe from 1.9 μm to 3.3 μm [3]. In 1995, Cr^{2+} ions doped II-VI crystals were proposed as promising broadly tunable mid-IR gain materials capable of lasing at room temperature [4,5]. Transitions to high-lying excited states are spin forbidden, which gives this laser advantages over earlier TM lasers such as Co^{2+} and Ni^{2+} [6,7]. Benefits of Cr:ZnSe lasers include compactness, up to 63% conversion efficiency [8], pure CW power up to 14 W [9,10], and pulsed average power up to 18.5 W [11]. However, the maximum gain-switched pulse energy with ns pulse durations has been limited to a few mJ for many years. The major problem with output energy scaling was in the development of fabrication technology for large-aperture, good optical quality, high optical density Cr:ZnSe gain elements. In this paper, we report on Cr:ZnSe crystals optimized for gain-switched pumping, as well as new peak power records for gain-switched Cr:ZnSe lasing pumped by Q-switched Cr:Tm:Ho:YAG (2.095 μm) and Raman shifted Nd:YAG lasers (1.907 μm).

2. GAIN ELEMENTS AND EXPERIMENTAL SETUP

One of the key elements of the energy scaling of nanosecond gain-switched Cr:ZnSe lasers is optimization of the gain medium. In this study we used Brewster cut Cr:ZnSe gain elements fabricated by IPG Photonics Corporation with a peak absorption coefficient (α) of 8-9 cm^{-1} at 1.78 μm, and $\alpha = 6$ cm^{-1} at pump wavelengths of 1.9 and $\alpha = 1$ cm^{-1} at 2.1 μm wavelength. Currently developed technology allows fabrication of large ($5 \times 5 \times 50$ mm^3) uniformly doped crystals. Figure 1 shows the fabricated gain elements and their measured absorption spectra.

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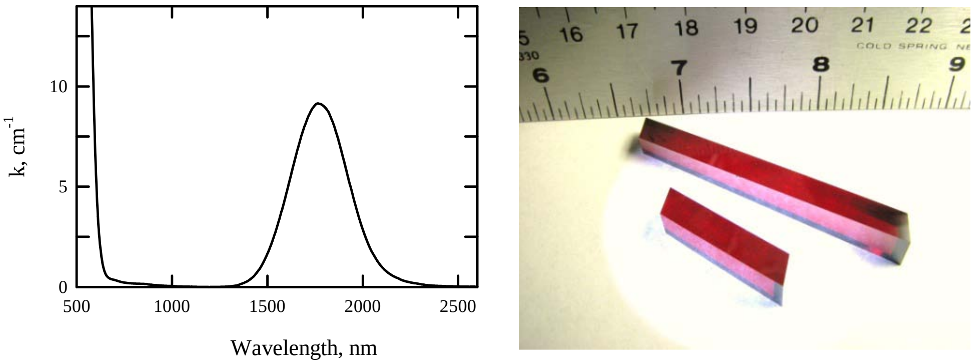

Fig 1. Absorption spectra of Cr:ZnSe gain elements (left) and their photograph (right).

The laser pump source is a critical element in design of high output energy Cr:ZnSe/ZnS lasers. The broad (1.4-2.1 μm) absorption band of Cr ions in the II-VI hosts shown in Figure 1 allows one to use multiple pump laser sources, however there is a trade space in pump wavelength. Pumping at the peak of absorption allows a smaller gain length, however heating will occur as the quantum defect is high. Pumping at longer wavelengths reduces the quantum defect; however, the absorption cross section is lower, which requires a longer crystal for efficient pump absorption.

The first pump source used for our gain-switched Cr:ZnSe laser experiments was a Cr,Tm,Ho:YAG laser (Schwartz Electro-optics, SEO). The laser pulse FWHM was 90 ns, and pulse characteristics include a wavelength of 2.095 μm and up to 13 mJ of pulse energy. The key element of the second pump laser was an injection seeded, single frequency Q-switched Nd:YAG laser (GCR-230-10, Spectra Physics) with a maximum output energy of 1.5 J at 1.064 μm, a linewidth of 0.003 cm^{-1}, 10 ns pulse duration and a repetition rate of 10 Hz. The 1.064 μm Nd:YAG radiation after passing through an optical isolator was focused by a 25 cm lens into a 50 cm long Raman cell filled with H_2 at a pressure of 800 psi. In backscattering geometry the output energy of the first Stokes line at 1.907 μm exceeded 300 mJ with 7 ns pulse duration at FWHM. However, to avoid optical damage of the crystal the maximum pump energy was limited in our experiments to 27 mJ.

For high pulse energy gain-switched laser design, the laser-induced damage threshold (LIDT) of the gain medium is a key constraint that guides cavity design. The LIDT for ZnSe has not been tested near a wavelength of 2 μm, but the LIDT can be estimated using its 10 μm values as both wavelengths are far from the linear, two-photon and three-photon absorption regimes. In [12], a 200 ps τ_p (FWHM) LIDT of 0.45 J/cm^2 and 100 ns τ_p (FWHM) LIDT of 2.8 J/cm^2 are reported for ZnSe. A $\tau_p^{0.3}$ scaling method fits these data points [13], resulting in a predicted LIDT of 1.8 (2.75) J/cm^2 for pump pulses of 7 (90) ns duration. These values do not include intra-cavity magnification induced by the outcoupler or absorption from the lightly-doped active ions. Additionally, the edges of the crystals are cut at the Brewster angle, which raises their damage threshold when compared to normal incidence due to an enlarged spatial profile in the crystal.

3. GAIN-SWITCHED Cr:ZnSe LASER PUMPED BY Q-SWITCHED Cr,Tm,Ho:YAG LASER

In the cavity design shown in Figure 2, *M1* is a 50 cm ROC mirror, d_1 is 7.5 cm, d_2 is 15 cm and the mode size was adjustable with a variable length d_1. Calculations predicted a $1/e^2$ mode radius of 600 μm at the planar outcoupler and 450 μm at the planar *M2* folding mirror. The pump was focused to a ~500 μm spot radius on the crystal using a 1 meter focal length lens placed 30 cm away. We used a sample which was 24 mm long, 4.7 mm high and tapered from 6.3 to 5.3 mm wide to prevent parasitic oscillations in the transverse direction.

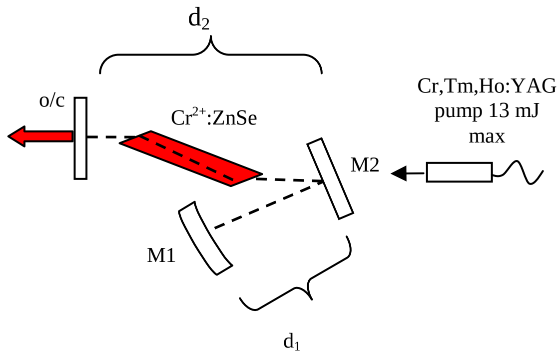

Fig. 2. Cavity design for Cr^{2+}:ZnSe gain-switched laser.

Lasing pulse energies using 50% and 70% outcouplers are presented in Fig. 3 along with their slope efficiencies. In order to measure lasing slope efficiencies, the incident pump pulse energy was calibrated to the reflection from a Thorlabs BP108 beam splitting pellicle, and Cr:ZnSe pulse energy was measured on an RJ-735 energy head and RJ-7620 ratiometer. Measurement of unabsorbed pump energy was performed over the range of pump powers by recording the laser output after dumping the Cr^{2+} emission away with a dichroic mirror. This unabsorbed pump energy varied from 5-15% of incident energy, and was subtracted from the incident pulse energy to yield the *absorbed pump* x-axis in Fig. 3.

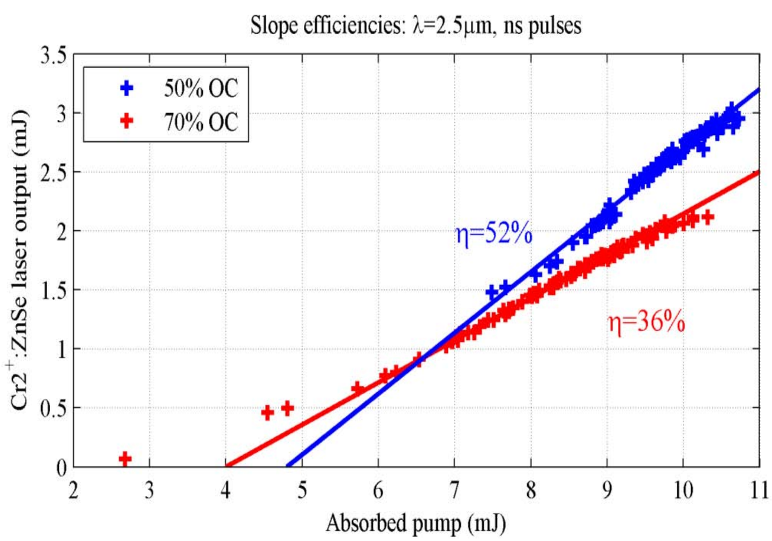

Fig. 3. Output-input (absorbed energy) characteristics of Cr,Tm,Ho:YAG laser pumped gain-switched Cr^{2+}:ZnSe laser.

The gain-switched temporal profile is shown in Fig. 4 for a 50% reflective outcoupler (blue) and a 70% reflective outcoupler (red). As the outcoupler reflectivity is reduced, the amount of energy in the secondary peak is shifted towards the primary peak. For this laser, a beam quality of M^2 = 1.4 was measured for both x and y axes, with a slight astigmatism. Fig. 4 (right) shows that the beam has a near-Gaussian spatial profile when focused to a 265 μm spot radius.

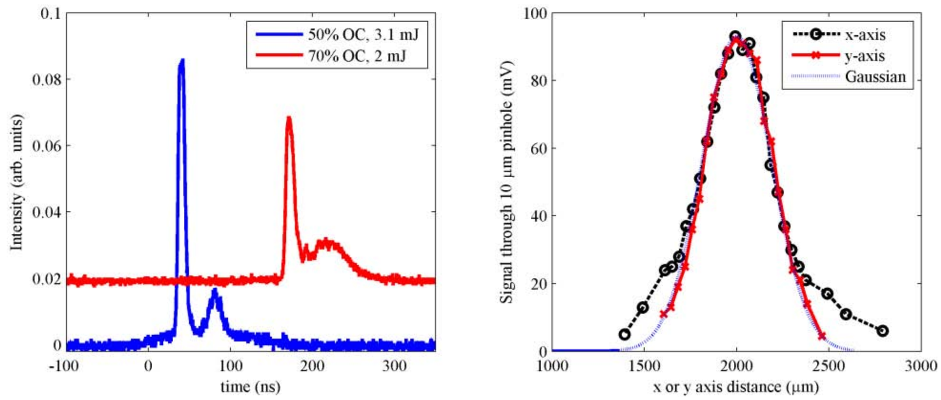

Fig. 4. Gain-switched Cr:ZnSe temporal profile where the 70% reflective outcoupler trace is offset for clarity (left), and spatial profile when focused to a 265 μm spot radius (right).

The spectral content of the pulses was measured with a monochromator (ARC, SpectraPro-750), where the spectrum was sampled at 0.2 nm increments from 2000-2800 nm. The resulting spectra are given in Fig. 5, showing a 2.47 μm peak emission, 110 nm linewidth (full width at 1/*e* pulse energy) and verifying that there is no 2.095 μm pump present. Additionally, the LEEDR-predicted atmospheric transmittance over a 2 meter path length [14]. is overlaid in black; clearly water absorption features limit spectral content at wavelengths longer than 2500 nm.

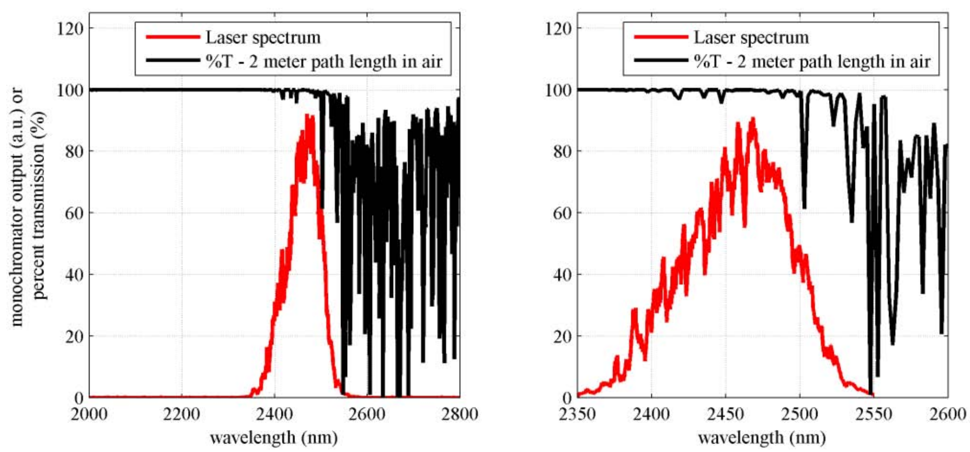

Fig. 5. Spectra of gain-switched Cr^{2+}:ZnSe laser output. (left) Complete spectra showing no 2.095 μm pump present, (right) zoomed in to show peak emission and linewidth.

4. GAIN SWITCHED Cr:ZnSe LASER PUMPED BY RADIATION OF FROM A H_2 RAMAN SHIFTED Nd:YAG LASER

To increase the output peak power and energy of the Cr:ZnSe laser we further studied its gain-switched oscillation under excitation with an H_2 Raman shifted Nd:YAG laser operating at 1.907 μm with 7 ns pulse duration. To minimize a cavity round-trip time we used a linear laser cavity design shown in Figure 6. The pump beam radius of ~3 mm was slightly focused by a 40 mm lens through a dichroic mirror (DM), which has a high reflectivity (R>99%)over the 2.25-2.5 μm range and ~80% transmission at the pump wavelength. The distance between the focusing lens and the input facet of the Cr:ZnSe crystal was 16 cm. It provided a pump beam diameter on the input crystal surface of ~2 mm. For 27 mJ pump energy, it results in below optical damage threshold energy flux of 0.9 J/cm^2 which is close to the value of the saturation flux ($\hbar\omega/\sigma_{ab}$) at 1.9 μm (σ_{ab} is absorption cross-section). We used Si and sapphire substrates as output couplers with effective reflectivity ~60% and ~13%, correspondingly. The output-input energy dependence is depicted in Figure 7A (right). As one can see from Figure 7A , the laser threshold was 2.1 and 4.1 mJ for Si and sapphire output couplers, respectively; the max output energy of 10.1 mJ was demonstrated for the sapphire output coupler. The slope efficiencies estimated from the data were 44% and 37% for sapphire and Si, correspondingly. The maximum output energy in our experiments was limited only by the surface LIDT of the active element. The FWHM of the output-pulse temporal-profile was shorter than 7 ns. The spectral content of the oscillation is shown in Figure 7B. The initial transmission of the gain element was $\sim 10^{-5}$ at 1.907 μm. We initially assumed that the absorption of unsaturated Cr^{2+} ions could result in a red shift of the oscillation wavelength. However, as one can see from the Figure 7B, the oscillation spectrum had a maximum at 2.35 μm with FWHM of ~110 nm.

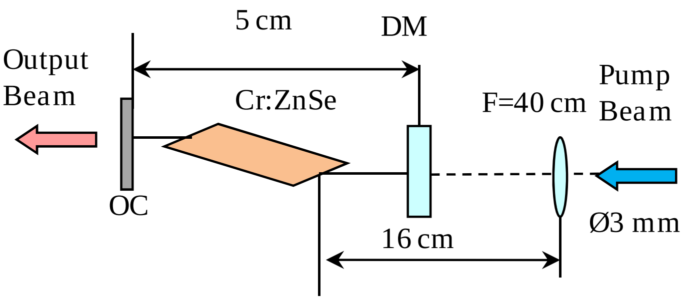

Fig. 6. Optical scheme of the Cr:ZnSe laser in the experiments with Raman laser pumping.

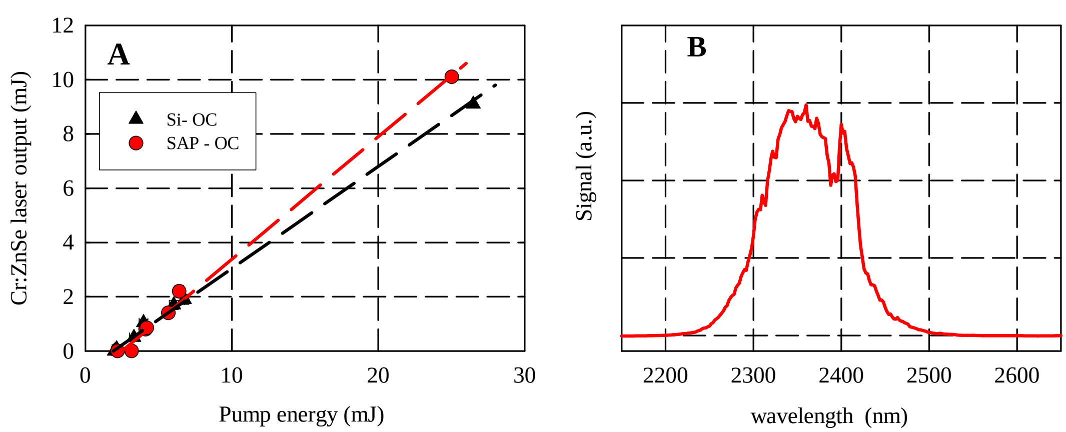

Fig. 7. Output energy of the Cr:ZnSe laser with Si (triangle) and Sapphire (circle) output couplers vs incident pump energy at 1.907 μm (A) and the output spectrum of the Cr:ZnSe laser (B).

5. CONCLUSIONS

We report record nanosecond output energies of gain-switched Cr:ZnSe lasers pumped by the radiations of Q-switched Cr:Tm:Ho:YAG and H_2 Raman shifted Nd:YAG lasers. It is noteworthy that the peak power demonstrated in the gain-switched oscillation mode significantly exceeds the peak power demonstrated in the mode-locked regime of oscillation of Cr:ZnSe lasers. Despite an ultrashort pulse width, the highest documented mode-locked peak power is much lower, due to small (≤ nJ) energies of individual pulses. The state-of-the-art output characteristics of these Cr:ZnSe lasers are summarized in Table 1.

Table 1. Cr^{2+}:ZnSe lasers, organized by peak power

Pulse energy	Pulse full width	PRF	Peak Power (W)	Mode of operation	Reference
-	-	-	12.5	CW	Moskalev [9]
-	-	-	14	CW	Berry [10]
14 mJ	120 μs	1Hz	117	GS	Koranda [16]
4 nJ	11 ps	100 MHz	364	ML	Pollock [17]
0.4 mJ	200 ns	10 kHz	2,000	GS	McKay [18]
375 pJ	100 fs	200 MHz	3,750	ML	Sorokina [19]
444 pJ	80 fs	180 MHz	5,556	ML	Sorokina [20]
2.6 mJ	100 ns	7 kHz	26,000	GS	Carrig [11]
3.1 mJ	60 ns	3 Hz	194,000*	GS	Present work (AFIT/AFRL)
2 mJ	7 ns	10Hz	286,000	GS	Gallian [15]
10.1 mJ	7 ns	10Hz	1,443,000	GS	Present work (UAB)

Legend: CW = continuous wave, GS = gain-switched, ML = modelocked, * calculated from actual temporal profile in Fig. 4

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